PROGRESS REPORT FORM

(via e-mail)

1. PI and Co-I Names and Affiliations:

PI: Anthony B. Davis, LANL, Space & Remote Sensing Group (NIS-2).

Co-I: Alexander Marshak, NASA-GSFC, Climate & Radiation Branch (code 913).

Co-I: Eugene Clothiaux, The Pennsylvania State University, Department of Meteorology.

2. Title of Research Grant:

Wavelet/Fractal Analyses and Modeling of Cloudiness and 3D Radiative Transfer Studies
in Support of DOE's ARM Program

3. Scientific Goal(s) of Research Grant (Maximum of 200-300 words)

a. Analysis and modeling of 3D shortwave radiative transfer effects due to clouds in ARM's quasi-pointwise measurements, at GCM grid-scales, and all scales in between. This is essentially continuity-in-spite-of-distance of my close collaboration with two ARM groups located at NASA-GSFC (PIs: Warren Wiscombe and Robert Cahalan). This collaborative work was initiated during my 5-year tenure there under ARM funding and, in this respect, their goals and ours are fully aligned.

b. Develop "next-generation" parameterizations of solar radiation transport for GCMs based on new analytical 3D radiative transfer theories that make predictions for domain-averaged radiation fields. Examples of such theories are anomalous/Lévy photon diffusion and Markovian/stochastic radiative transfer formulated in the two-stream approximation. Characteristically, these models are not yet fit to be inserted into GCMs nor partake in the on-going ICRCCM (Inter-Comparison of Radiation Codes for use in Climate Models) revival. However, and unlike most current parameterizations, they can be applied to and successfully explain radiative observations such as time-series of surface flux and joint pathlength/LWP statistics.

c. Develop approximate-but-efficient 3D radiative transfer codes to be used in LES and CRM simulations. These important dynamical tools in the overall ARM program resolve 3D structures that are responsible for exciting significant horizontal radiative fluxes in clouds but ignore them in their energetics. The best way to estimate and eventually remove these local heating-rate biases is give the radiation schemes full 3D capability, at a small cost in computer time of course. The necessary accuracy/efficiency trade-off study will be performed in the frame of the Intercomparison of 3D Radiation Codes (I3RC).

d. The PI has been tasked by the former and new ARM Chief Scientists to organize an event (conference or workshop) that promotes productive relationships between “mainstream” atmospheric scientists and experts in fractal (and otherwise nonlinear) methods. Here, “productivity” is measured by success in helping to solve current problems in atmospheric science.

4. Accomplishments in “Bulletized Form.” Just a sentence or two description of specially significant results obtained in the previous twelve months.

Using the same *a-d* breakdown as in the above statement of goals:

a. Analysis and modeling of 3D radiative transfer effects in clouds: (1) definition of the Normalized Difference Cloud Index” (NDCI) and application to cloud remote sensing, and (2) diffusion theory of radiative smoothing at absorbing wavelengths that controls the magnitude of 3D effects in satellite remote sensing of stratiform clouds.

b. Anomalous diffusion model for shortwave radiation transport: (1) validation using time-domain optical lightning data from DOE’s Fast On-orbit Transient Experiment (FORTÉ) satellite, and (2) formal connection between Gamma distributions of optical depth observed in Landsat scenes and mean transport kernels with power-law decays.

c. Fast-but-approximate 3D radiative transfer computations: (1) two contributions of this type, as well as a representative slow-but-exact one, to I3RC - Phase 1; (2) PI leads two subtasks in I3RC-Approximations, one for deterministic (given cloud) modeling, one for mean-field (given cloud statistics) modeling.

d. Venue for productive dialog between fractal experts and atmospheric scientists: (1) exploration of AGU Chapman Conference format; (2) consensus on a less ambitious proposal of a special session during Spring'01 AGU Meeting, possibly as a stepping-stone towards an independent (Chapman?) event.

5. Progress and accomplishments during last twelve months (or from beginning of the current effort whichever is shorter). Expectation here is no less than one page and no more than 5 pages double-spaced. Not counting figures/graphics.

Using the same *a-d* breakdown:

a. Analysis and modeling of cloudiness variability and associated 3D radiative transfer

This is the "core" aspect of the grant which was originally designed in mid-98 to enable the PI to carry on from Los Alamos National Laboratory the close collaboration with Warren Wiscombe, Alexander Marshak, Robert Cahalan, and their collaborators at NASA-GSFC. The tangible outcome of this collaboration this year is in referred paper [2] and extended abstract #3 for the data analysis and modeling. Also of note was a round of commentary-and-reply to an ARM-related paper on marine BL cloud structure that appeared in JGR early '99; this publication project was aborted by the JGR editor in view of a poor external review of the commentators' critique of our original work. Turning to 3D radiative transfer studies, the collaboration has produced this year papers [1,3] and abstracts #1,7. The significant results are: (1) theory and validation of the NDCI, a radiometric trick for removing 3D radiative transfer effects even under broken cloud layers from (vegetated) ground-level zenith radiances at VIS and NIR wavelengths and, from there, retrieving cloud optical depths; (2) radiative smoothing theory in the presence of absorption using diffusion methods and application to sub-pixel effects in cloud remote sensing from space. As expected, unresolved 3D effects are reduced in channels with liquid water absorption (see attached figure).

The strategy formulated back in '98 was (*i*) to pursue the overlapping radiative transfer work at a distance and (*ii*) to take all of the wavelet/fractal data analysis and cloud modeling part of the collaborative project to LANL, with the explicit goal to adapt it to ARM's MMCR anisotropic 2-dimensional data-stream. This is why Eugene Clothiaux from PSU was recruited as a Co-I with considerable hands-on MMCR expertise. The analysis algorithms where indeed developed early in FY99 and tested on artificial data (cf. last year's progress report). However, the well-documented problems that plagued the MMCRs prevented the planned phase of extensive data analysis from starting until now. In the meantime, a data/software exchange protocol has been established between LANL and PSU, where Dr. Kristinka Ivanova will be performing the analyses per se and reporting to the investigators on this grant. This is a near-optimal arrangement since she is well-versed in multifractal analysis techniques at least in 1D. In fact, Dr. Ivanova has published this year a joint paper [5] using several time-series of ARM MWR data to describe, in spatial statistics terms, the transition from stratiform to broken cloudiness.

For the second half of FY99 and much of FY00, the slow progress on the MMCR data analysis front enabled the PI to make significant advances in radiative transfer problems that matter for the ARM program, and to take on some organizational tasks. Accomplishments in these areas are described in the following three subsections.

b. <u>Next-generation parameterizations of shortwave radiation transport in GCM columns</u>

The main motivation here is the rather surprising success of the anomalous photon diffusion model in explaining observations of solar pathlengths (from high-resolution O_2 A-band spectroscopy) at given total-column optical depth [Pfeilsticker, *J. Geophys. Res.*, *vol. 104*, 4101-

4116, 1999]. In anomalous diffusion, photons make random jumps that deviate strongly from the Gaussian (or otherwise narrow) distributions that define standard diffusion; this generalization of diffusion theory captures in a 1D setting the major effects of 3D variability in cloudiness. To date, we have assumed Lévy-stable distributions for their power-law tails and their analytical properties. Since the new model ignores the details of the 3D radiative transfer and deals only with large-scale quantities, it is a prime candidate for spawning new GCM parameterizations. However, it presently lacks a clear analytical formulation that could be used to predict fluxes and heating-rates in the cloudy column, so we think of it as a parameterization "in the making."

This year, it has been established that the anomalous/Lévy model provides a natural explanation for the phenomenology of lightning observations from space according to DOE's nonproliferation satellite mission FORTÉ (science team is at LANL/NIS-1). Indeed, the portion of the delay in arrival time of optical lightning signals (with respect to RF) due to multiple scattering is as the new model predicts, given reasonable assumptions on the outer thickness of the (stormy) cloud system and its optical depth averaged over the radiative smoothing scale for transmission. An account of this new empirical validation of the model will appear in extended abstract #2 (see attached figure).

Finally, one of the missing links in evolving the new transport model into a GCM parameterization is a way of predicting its variability parameter (the Lévy index α) from metrics of cloud variability. Recently, progress has been made here by showing that the Gamma distributions in optical depth observed by Barker et al. in Landsat images [*J. Atmos. Sci.*, *vol. 53*, 2304-2316, 1996] yield precisely the transport kernels that lead to anomalous diffusion. A paper on this finding is already drafted.

Another 3D radiative transfer model with parameterization potentiality is "stochastic" radiative transfer for Markovian media. This model was pioneered by Georgii Titov, Gerald Pomraning, and Nelson Byrne to mention only a few more-or-less related to the ARM program. Tragically, both Titov and Pomraning died of cancer in '98 and '99 respectively. Fortunately, Byrne's work has been continued at Scripps by Richard Sommerville and his PhD student Dana

Lane who used ARM data to prescribe model parameters and made consistency checks with radiometry. In the 2-stream approximation, this model becomes analytically tractable. The PI is now in collaboration with Y.-X. Hu of NASA's Langley RC, another proponent of Markovian/stochastic modeling, to pursue this route towards another GCM parameterization that accounts for sub-grid variability.

c. Approximate-but-efficient 3D radiative transfer codes

The PI and co-I Marshak are on the executive committee of the I3RC initiative in computational 3D radiative transfer spearheaded by Robert Cahalan (NASA/GSFC) with partial support from ARM. This entails a considerable amount of consultation work to define representative input models and output radiation fields, as well as methods for processing these outputs that enhances the utility of the intercomparison.

Apart from this organizational work, the PI has secured the help of Drew Kornreich (LANL/TSA-7), Charles Rohde (LANL/NIS-2) and Zheng Qu (CIRES) to contribute model output to I3RC from key regions of model-space that were poorly represented in the remainder of the line-up. In particular, approximate models that deliberately trade accuracy for speed are an important asset in 3D radiative transfer (see attached figure). Extended abstracts #4, #5, and #6 describe these I3RC contributions.

The question of efficiency becomes especially important when it comes to certain applications of (read "clients for") 3D radiative transfer. For instance, LES modeling is likely to be quite sensitive to the biases in local heating-rates introduced by using 1D (plane-parallel) theory in a medium with structures that are known to generate strong horizontal radiative fluxes. To test this hypothesis, the PI and Bob Cahalan have started a project in collaboration with Yefim Kogan's (ARM-funded) LES group at Un. of Oklahoma, including Evgeni Kassianov (now at PNNL). The LES group will prepare their model for running interactively with 3D radiative transfer using slow-but-sure Monte Carlo methods. In parallel, the PI will rally diffusion-based radiation modelers (Zheng Qu and, hopefully, also Yu Gu and K.-N. Liou from

UCLA) to develop efficient 3D codes. Post-diffusion approximations such as "discrete-angle" radiative transfer will also be considered.

I3RC is the natural framework to study accuracy/efficiency tradeoffs, and the PI has taken the lead in the I3RC subtask on "Approximations:"

http://climate.gsfc.nasa.gov/I3RC/approximations.html

Currently, this subtask contains models that can compute radiation fields for any given cloud structure (e.g., 3D diffusion theory as described above) as well as "mean-field" models that only make predictions for the largest scales and for a whole class of statistically related media at that (e.g., Markovian stochastic radiative transfer discussed in item *b.*). The latter should be moved over to ICRCCM-3 in a loose category of innovative models that can lead to GCM radiative parameterizations; negotiations on this move have been initiated with the main ICRCCM-3 organizer, Howard Barker. The remaining "deterministically" approximate models will stay within I3RC but can not be held to the same time-line as regular participants because of their significant overhead in development and implementation.

d. Organization of a "fractals-at-work" event

With the help of Gerry Stokes and Evgeni Kassianov, the PI and co-I Alexander Marshak organized a very successful session at AGU's 1999 Spring Meeting in Boston on atmospheric 3D radiative transfer; this special session was actually convened to honor the memory of our friend and colleague Georgii Titov who had passed away in 1998. There was also a follow-on workshop on the same topic held at UMBC/JCET. For more information on these events, we refer to the summary that appeared recently in Eos [4].

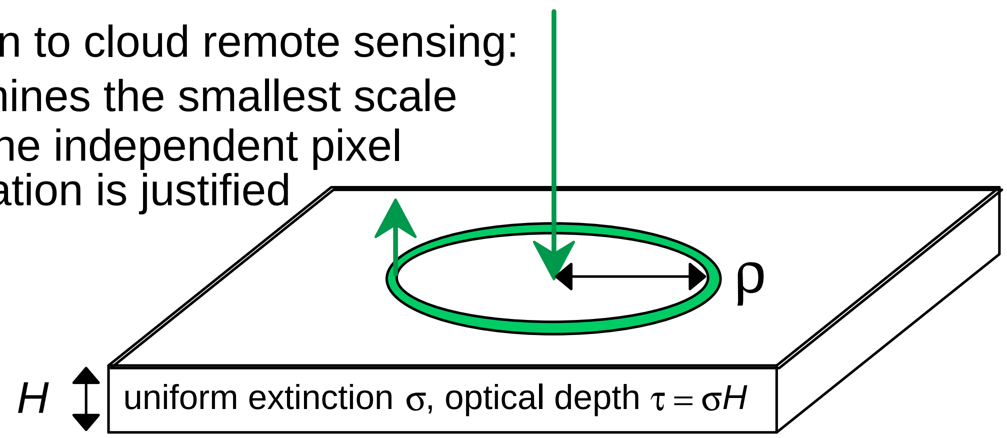
In the wake of this success, Gerry Stokes and his successor as ARM Chief Scientist Tom Ackerman asked the PI to plan another meeting, this time on applications of fractal concepts to current problems in atmospheric science. Emphasis here is on "application" or "help." This type of effort is to be contrasted with exercises based on atmospheric data analyses that invariably lead to the conclusion that the atmosphere is so inherently fractal that current methods in meteorology are essentially doomed, with no hope of redemption whatsoever. So there is a need to re-establish a productive dialog between two somewhat estranged communities: fractal experts and "mainstream" atmospheric scientists. The desirable time-frame for this "reconciliation" event is sometime in FY01. Progress towards this goal is marked by the following milestones:

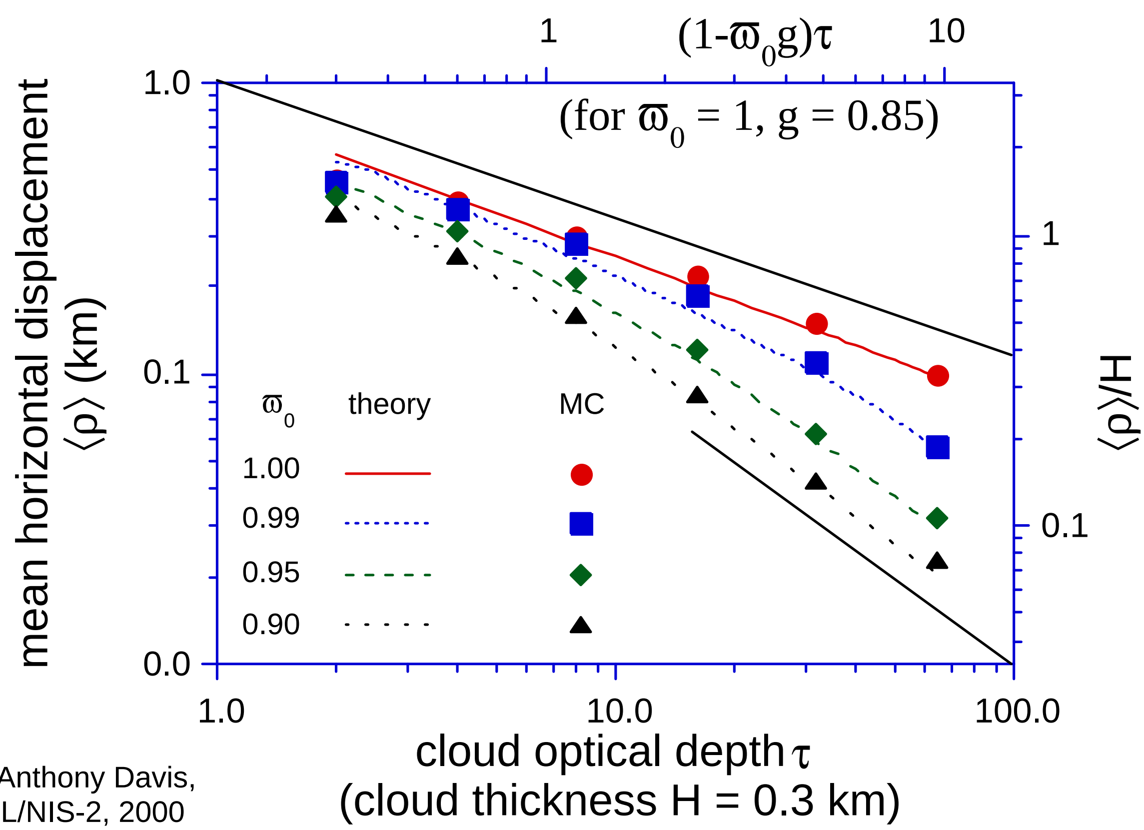
- exploration of the idea of an AGU Chapman Conference in consultation with ARM Chief Scientist;
- decision to down-scale to another special session at an AGU Meeting (possibly as stepping-stone towards the more ambitious stand-alone Chapman conference);
- representative convening team was composed and a proposal drafted for joint session co-sponsored by AGU's new Technical Committee on Nonlinear Geophysics ("NG") of which the PI is member and the Atmospheric Science ("A") Section;
- decision (against advice from NG Committee Chair) to postpone the session from Fall'00 to Spring'01, with the same conveners and description, as suggested by Tom Ackerman.

6. **As appropriate attach one or so electronic figures with paragraph discussions highlighting current research.** Label with PI name, affiliation, and year. We will use these in presentation materials.

Radiative smoothing scale for stratiform clouds: diffusion theory & numerical simulations

Application to cloud remote sensing:
⟨ρ⟩ determines the smallest scale
at which the independent pixel
approximation is justified

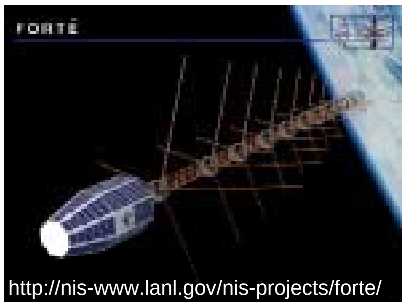


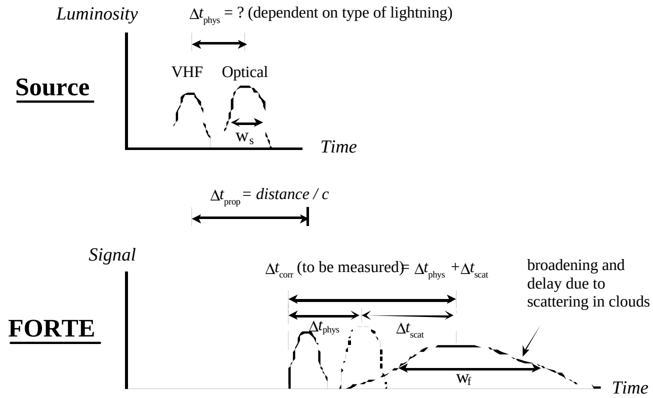


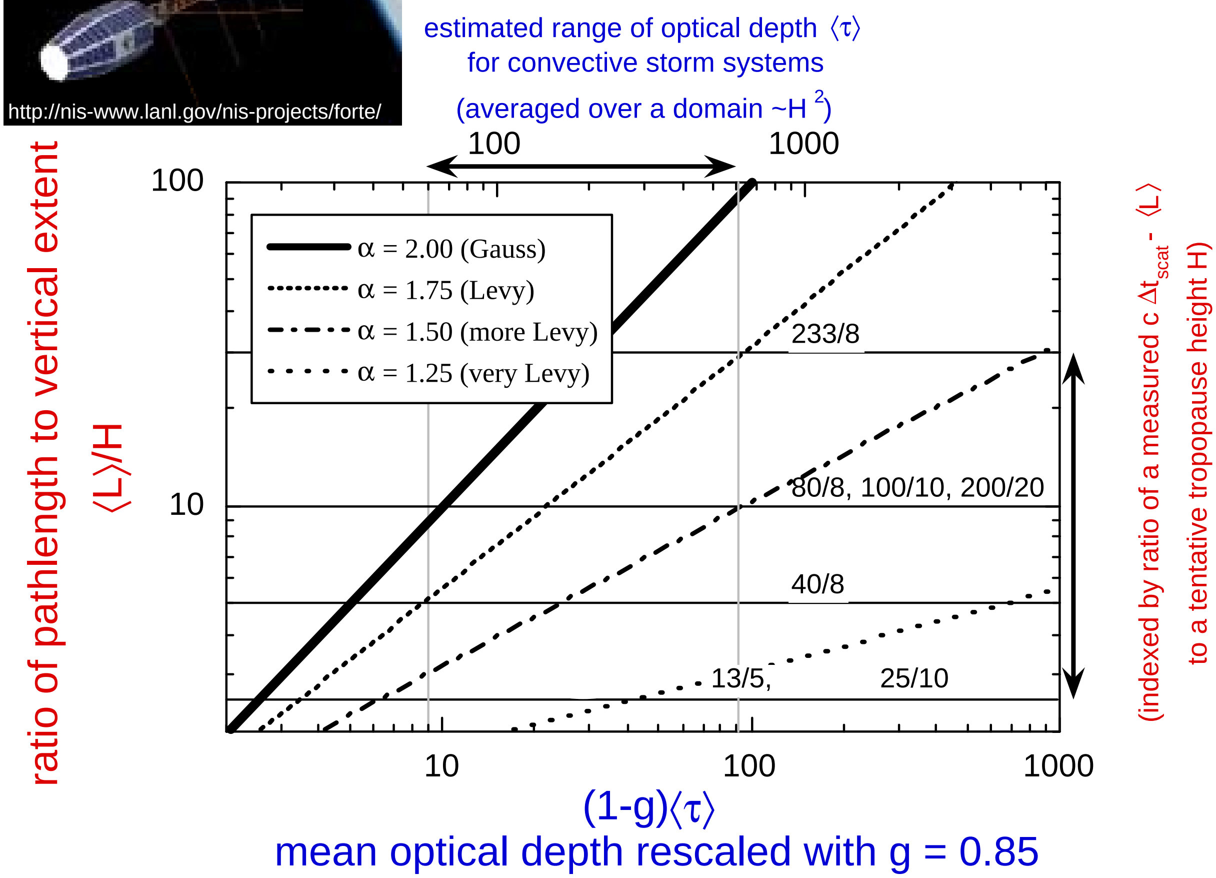
PI: Anthony Davis,
LANL/NIS-2, 2000

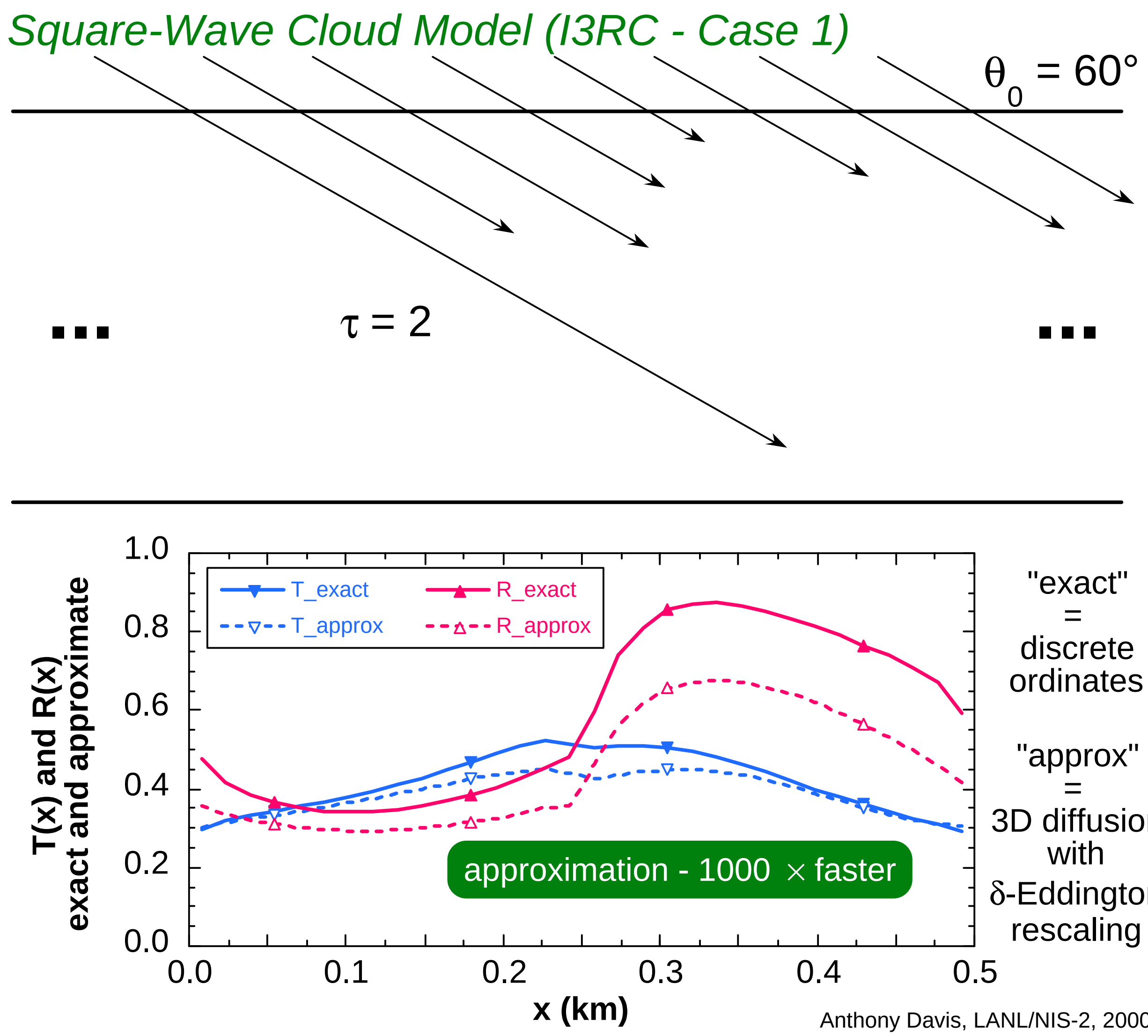
Anomalous/Lévy diffusion theory & optical lightning waveforms from FORTÉ

PI: Anthony Davis, LANL/NIS-2, 2000









Square-Wave Cloud Model (I3RC - Case 1)
θ0 = 60°
...
τ = 2
...
T_exact
R_exact
T_approx
R_approx
1.0
0.8
0.6
0.4
0.2
0.0
T(x) and R(x)
exact and approximate
0.0
0.1
0.2
0.3
0.4
0.5
x (km)
approximation - 1000 × faster
"exact"
=
discrete
ordinates
"approx"
=
3D diffusion
with
δ-Eddington
rescaling
Anthony Davis, LANL/NIS-2, 2000

7. **List all *refereed* publications either submitted or published during the *current* grant FY that acknowledge DOE ARM support.** Two copies of all submitted papers should accompany the progress report. (Via ordinary mail: Two reprints of all published papers should be submitted to the ARM Science Director when reprints are received. If this wasn't done at the time please include reprints with the progress report.)

R[1] MULTIPLE SCATTERING IN CLOUDS: INSIGHTS FROM THREE-DIMENSIONAL DIFFUSION/P_1 THEORY, **A. B. Davis**, and A. Marshak, *Nucl. Sci. Eng.*, Special Issue "In Memory of Gerald C. Pomraning" (accepted).

COMMENT ON "HORIZONTAL STRUCTURE OF MARINE BOUNDARY LAYER CLOUDS FROM CENTIMETER TO KILOMETER SCALES;" H. Gerber, and **A. B. Davis**, *J. Geophys. Res.* (submitted).

[2] SPECTRAL DENSITIES OF CLOUD LIQUID WATER CONTENT AT HIGH FREQUENCIES, H. Gerber, R. Boers, J. B. Jensen, **A. B. Davis**, A. Marshak, and W. J. Wiscombe, *J. Atmos. Sci.* (accepted).

EPLY TO [3] CLOUD – VEGETATION INTERACTION: USE OF NORMALIZED DIFFERENCE CLOUD INDEX FOR ESTIMATION OF CLOUD OPTICAL THICKNESS, A. Marshak, Y. Knyazikhin, **A. B. Davis**, W. J. Wiscombe, and P. Pilewskie, *Geophys. Res. Lett.*, *vol. 27*, 1695-1698.

[4] THREE-DIMENSIONAL RADIATIVE TRANSFER MAKES ITS MARK! (Summaries of special session on "Three-Dimensional Radiative Transfer in the Cloudy Atmosphere, A Tribute to Georgii Titov (1948-1998)" at AGU Spring'99 Meeting and JCET International Workshop on "Radiative Transfer in the Inhomogeneous Cloudy Atmosphere"), **A. B. Davis**, A. Marshak, E. Kassianov and G. M. Stokes, *Eos (AGU Transactions)*, *vol. 80*, 622–624, 1999.

[5] ATMOSPHERIC DATA ANALYSIS WITH THE *I*-VARIABILITY DIAGRAM METHOD: HINT TO FRACTIONAL BROWNIAN MOTION-LIKE PHENOMENA FOR THE INNER STRUCTURE OF CLOUDS, K. Ivanova, M. Ausloos, **A. B. Davis**, T. Ackerman, *Physica A*, *vol. 272*, 269–277, 1999.

8. **List all published (either paper or web-based) extended abstracts in the current FY that acknowledge DOE ARM support.** (Via ordinary mail: Two copies of each should accompany the progress report.)

1. THE USE OF REFLECTION FROM VEGETATION TO ESTIMATE BROKEN-CLOUD OPTICAL PROPERTIES FROM SURFACE ZENITH RADIANCE MEASUREMENTS, W. J. Wiscombe, A. Marshak, Y. Knyazikhin, and **A. B. Davis**, in *Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, 03/13–17, 2000, San Antonio (Tx), U.S. Dept. of Energy, available on-line at http://www.arm.gov/docs/documents/technical/conf_0003/wiscombe-wj.pdf.

2. SHORTWAVE TRANSPORT IN THE CLOUDY ATMOSPHERE BY ANOMALOUS/LÉVY PHOTON DIFFUSION: NEW DIAGNOSTICS USING FORTÉ DATA, **A. B. Davis**, D. M. Suszcynski, and A. Marshak, in *Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, 03/13–17, 2000, San Antonio (Tx), U.S. Dept. of Energy, in preparation for on-line publication.

3. MARINE BOUNDARY-LAYER CLOUD STRUCTURE FROM KM- TO CM-SCALES, **A. B. Davis**, H. Gerber, and A. Marshak, in *Proceedings of 13th International Conference on Clouds and Precipitation*, Reno Area (Nevada), August 14–18, 2000, in press.

4. APPROXIMATING 3D RADIATIVE TRANSFER IN CLOUDS WITH DIFFUSION THEORY, **A. B. Davis**, and Z. Qu, in *Proceedings of First International Workshop on Intercomparison of 3D Radiation Codes (I3RC)*, Nov. 17–19, 1999, Tuscon (Az), available on-line at http://climate.gsfc.nasa.gov/I3RC/workshopreports.html (click "LANL1").

5. DISCRETE-ANGLE RADIATIVE TRANSFER: IMPROVING ON DIFFUSION THEORY? **A. B. Davis**, in *Proceedings of First International Workshop on Intercomparison of 3D Radiation Codes (I3RC)*, Nov. 17–19, 1999, Tuscon (Az), available on-line at http://climate.gsfc.nasa.gov/I3RC/workshopreports.html (click "LANL2").

6. ANALYSIS OF THE I3RC TWO-DIMENSIONAL STEP-CLOUD PROBLEM WITH TWODANT, D. E. Kornreich, **A. B. Davis**, and C. A. Rohde, in *Proceedings of First International Workshop on Intercomparison of 3D Radiation Codes (I3RC)*, Nov. 17–19, 1999, Tuscon (Az), available on-line at http://climate.gsfc.nasa.gov/I3RC/workshopreports.html (click "LANL3").

7. ERROR ESTIMATION IN THE MONTE CARLO METHOD FOR COMPUTING RADIANCES: ILLUSTRATION WITH CLOUD MODELS BASED ON LANDSAT MEASUREMENTS, A. Marshak, **A. B. Davis**, L. Oreopoulos, and T. Varnaì, in *Proceedings of First International Workshop on Intercomparison of 3D Radiation Codes (I3RC)*, Nov. 17–19, 1999, Tuscon (Az), available on-line at http://climate.gsfc.nasa.gov/I3RC/workshopreports.html (click "UMBC1").

9. Please update us on the status of submitted referred publications from the previous FY progress report. (If none, note "NONE")

The following paper was previously cited as "in press:"

ON THE REMOVAL OF THE EFFECT OF HORIZONTAL FLUXES IN TWO-AIRCRAFT MEASUREMENTS OF CLOUD ABSORPTION, A. Marshak, W. J. Wiscombe, **A. B. Davis**, L. Oreopoulos, and R. F. Cahalan, *Quart. J. Roy. Meteor. Soc.*, *vol. 125*, 2153–2170, 1999.